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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The title of this research contract describes the initial work done under the contract; after 1980 the research program was extended to the study of the primary decomposition of energetic materials and the dynamics of concerted reactions of organic molecules through cyclic transition states.  (continued on reverse)		

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## 20. Abstract (Continued)

Several reactions of fluorine atoms, fluorine molecules and other halogens were studied using the crossed molecular beams method. The system  $F + CH_3I$  allowed the study of the lifetime of and energy randomization in the  $CH_3IF$  reaction intermediate before dissociation. A method for synthesizing previously unobserved chemically reactive radicals and measuring their stability was made possible by using a seeded supersonic beam source to promote endothermic reactions at higher translational energies. Through the endoergic reaction of  $F_2$  with  $I_2$ ,  $ICl$  and  $HI$  the radicals  $I_2F$ ,  $ClIF$  and  $HIF$  were synthesized and their  $IF$  bond energies measured. In these studies a new mechanism of bimolecular reactions was also elucidated for the reaction  $F_2 + I_2 \rightarrow I_2F + F$ , and the relative yields of this reaction and the reaction  $F_2 + I_2 \rightarrow I + IF + F$  as a function of collision energy was investigated.

Several important techniques were developed during the contract period for the molecular beam experiment. The developments of a high pressure oxygen atomic supersonic plasma beam source allowed a series of mechanistic studies of oxygen atoms with unsaturated hydrocarbons. A molecular beam photoionization apparatus was also constructed in order to have an independent method to verify various reaction products observed in the crossed molecular beams experiments. A supersonic atomic and molecular halogen nozzle beam source was developed to produce high intensity beams of chlorine, bromine and iodine.

The reaction of  $O$  atoms with unsaturated and saturated hydrocarbons and halogenated molecules were studied. The primary reaction channels in the reaction of  $O(^3P)$  with  $C_6H_6$  and  $C_6D_6$  were identified and the branching ratio between the product channels was investigated as a function of collision energy and isotopic substitution. The products  $CH_3O + H$  were found to be the major ones in the important reaction of  $O(^1D) + CH_4$ . The study of the reaction  $O + ICl$  and  $O + CF_3I$  allowed determination of the  $IO$  bond strength and modelling of the second reaction as proceeding through a long lived complex.

→ The studies of the primary photodissociation of polyatomic molecules have been directed toward answering questions related to the primary decomposition of energetic materials and the dynamics of concerted reactions. A combination of the techniques of infrared multiphoton excitation and the molecular beam method has been used to carry out a series of these studies. In particular, the competition between simple bond fission reactions and concerted reactions were studied in detail in the infrared multiphoton dissociation of ethyl vinyl ether and diethyl ether. The primary photodissociation of ozone was studied as it is important both as a test for theoretical models and as a source of  $O(^1D)$  atoms in the atmosphere. The photodissociation of the energetic molecules nitromethane was investigated at 266 and at 193 nm. While no significant ( $\approx 3$  percent) dissociation occurred at 266 nm, the 193 excitation led to dissociation to  $CH_3$  and  $NO_2$  with a large fraction of the  $NO_2$  product being electronically excited and highly vibrationally excited. The photodissociation of ketene allowed a determination of the singlet-triplet splitting in methylene.

In order to study the primary dissociation processes of non-volatile compounds a new molecular beam apparatus, equipped with a rotatable beam source and a fixed ultra-high vacuum mass spectrometer, was designed and is now under construction. After completion this machine will be used for another ONR research contract which is essentially the continuation of this contract.

Final Technical Report  
Prepared for the

Office of Naval Research  
Arlington, Virginia

by

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CROSSED MOLECULAR BEAM STUDIES OF THE REACTIONS OF  
OXYGEN AND FLUORINE ATOMS

Period of Contract: April 1, 1975 to September 30, 1983

Contract Number: N00014-75-C-0671

## INTRODUCTION

The title of this research contract does not fully represent the contents of our research work carried out under this contract.

We initiated this program by investigating the reactions of fluorine atoms. After the discovery of new and exciting reactions involving fluorine molecules at higher translational energies, we applied this method to the synthetic and energetics studies of fluorine containing radical molecules. In order to make some meaningful comparison, reactions involving other halogen atoms were also carried out by using the crossed molecular beams method.

Much effort was devoted to the development of various techniques for new molecular beams experiments. The successful development of the oxygen atom beam source has been important for a series of mechanistic studies involving oxygen atoms with unsaturated hydrocarbons. In order to probe the content of the oxygen atom beam source, a photoionization molecular beam apparatus was constructed, which was found to be quite useful in the later investigation of the energetics of molecular ions. For the possible production of an  $O(^1D)$  beam source by the photodissociation method, we initiated molecular beam photofragmentation translational spectroscopy experiments to study for the dissociation of ozone and other molecules.

Since 1980, with the agreement of our program monitor, the direction of our program has changed to emphasize the decomposition of polyatomic molecules. Especially questions relating to the primary decomposition of energetic materials and the dynamics of concerted reactions in general have

been the objectives. We used the combination of infrared multiphoton excitation and the molecular beam method to carry out this series of studies.

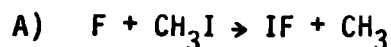
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## TECHNICAL PROGRESS SUMMARY

### 1) Reaction of Fluorine Atoms, Fluorine Molecules and Other Halogen Atoms.



Reaction dynamics, the lifetime of reaction intermediate  $CH_3IF$  and the extent of energy randomization in the  $CH_3IF$  complex before decomposition were investigated in great detail.

### B) Stability of Fluorine Containing New Radicals

A high energy  $F_2$  molecular beam source developed under the ONR contract enabled us to develop a new synthetic method for the study of chemically reactive radicals that had not been observed previously.

Through high energy endoergic reactions of  $F_2$  with  $I_2$ ,  $ICl$  and  $HI$ , we have successfully synthesized  $I_2F$ ,  $ClIF$  and  $HIF$  radicals. From the threshold energies of formation of these compounds IF bond energies are determined to be 33, 31 and 19 kcal/mole for  $I_2F$ ,  $ClIF$  and  $HIF$ .

### C) New Mechanism of Bimolecular Reactions

In the study of fluorine containing radicals, the stability of  $I_2F$  surprised us immensely. We didn't expect that the IF bond strength in this molecule would be as large as 33 kcal/mole, nor that the reaction  $I_2 + F_2 \rightarrow I_2F + F$  would proceed at such a low energy (~4 kcal/mole).

It is usually assumed that halogen molecule exchange reactions proceed either through four center bimolecular reactions or atom molecule reactions followed by initial dissociation of diatomic molecules into atoms. The



reaction, such as,  $I_2 + F_2 \rightarrow I_2F + F$  had not been speculated in the past. This is mainly due to our lack of knowledge of the nature of chemical bonding and the information on the stability of  $I_2F$  radical.

We have investigated collisions between  $F_2$  and  $I_2$  as a function of collision energies. Indeed, the formation of  $I_2F$  and the simultaneous generation of  $F$  is the reaction channel which proceeds at lowest collision energy. When the kinetic energy is more than 7 kcal/mole  $F_2 + I_2 \rightarrow I + IF + F$  channel becomes more important.

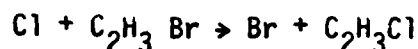
D) A Crossed Molecular Beam Study of the  $Cl + Br_2 \rightarrow BrCl + Br$   
Reaction

We have completed a crossed molecular beam study of the  $Cl + Br_2 \rightarrow BrCl + Br$  reaction at several collision energies. Angular distribution as well as velocity distributions of the scattered  $BrCl$  product have been measured.

The results of this work and the results of an investigation of this reaction at lower collision energy (~3.0 kcal/mole) seem to indicate that the  $Cl + Br_2$  reaction occurs on an attractive energy surface without any appreciable activation energy or barrier. Although the  $Cl + Br_2$  interaction seems to be an attractive one, the total reactive cross sections are much smaller than hard sphere values. The sharp recoil energy distribution at the high collision energy, peaking at 14 percent of the total available energy, seems to indicate that the reaction is approaching the spectator stripping model, which predicts a unique recoil translational energy, 11 percent of total available energy at this collision energy.

E) Energy Randomization in the  $\text{Cl} + \text{C}_2\text{H}_3\text{Br} \rightarrow \text{Br} + \text{C}_2\text{H}_3\text{Cl}$   
Reaction

When unimolecular processes are studied under single collision conditions, product energy distributions can yield information about the reaction dynamics. In chemiluminescence experiments with the reaction



Durana and McDonald found a product vibrational energy distribution which was inconsistent with a complete randomization of energy in the intermediate complex. On the other hand, Cheung et al. found in crossed molecular beam experiments that the product translational energy distribution for this reaction agreed with the predictions based on a statistical model. This apparent contradiction in product energy distributions led us to study the reaction using crossed supersonic beams with relatively low velocity spreads. The high average translational energy release observed in our experiment shows that this reaction cannot be treated with a purely statistical model.

2) Development of Experimental Methods and Technologies

A) Development of a High Pressure Oxygen Atom Supersonic Plasma Beam Source

A high pressure (supersonic) radio frequency discharge beam source has been developed which is capable of producing a high intensity beam of ground-state oxygen atoms. Impedance matching of the RF to the inductively

coupled plasma, as a function of both gas pressure and composition, allows for routine operation of the beam source with a standing wave ratio of less than 1.05:1. Preliminary results on beam characterization and O - He elastic scattering experiments are reported. In particular, molecular oxygen dissociation on the order of 80 - 90 percent has been observed in these initial (low-power) studies.

#### B) Molecular Beam Photoionization Apparatus

In the reaction of oxygen atoms with unsaturated hydrocarbons, it is very common to have several reaction channels taking place simultaneously. In order to have an independent method to verify various reaction products observed in the electron bombardment mass spectrometric detector in a cross molecular beam experiment, a molecular beam photoionization apparatus was constructed. This apparatus is equipped with a 1-m vacuum UV monochromator which has been in full operation with a new automatic wave length scanning and data acquisition device. While the oxygen atom beam source was being developed, several experiments were carried out to demonstrate the unique capability of this apparatus.

#### C) A Supersonic Atomic and Molecular Halogen Nozzle Beam Source

A reliable, resistance heated, nozzle beam source is described which is capable of producing high intensity supersonic atomic and molecular beams of chlorine, bromine, and iodine. The use of a high density graphite nozzle eliminates corrosion and allows for operation up to 2100K. The performance of this source is reported using seeded halogen gas mixtures which extend the accessible kinetic energy region to several eV.

### 3) Reaction of Oxygen Atoms

#### A) A Crossed Molecular Beam Investigation of the Reactions $O(^3P) + C_6H_6, C_6D_6$

A crossed molecular beam investigation of the reactions of  $O(^3P) + C_6H_6, C_6D_6$  has been carried out using a seeded, supersonic, atomic oxygen nozzle beam source. Angular and velocity distributions of reaction products have been used to identify the major reaction pathways. The initially formed triplet biradical,  $C_6H_6O$  ( $C_6H_6O$ ), either decays by hydrogen (deuterium) elimination or becomes stabilized, most likely by nonradiative transition to the  $S_0$  manifold of ground state phenol. CO elimination was not found to be a major channel. The branching ratio between H(D) atom elimination and stabilization was found to be sensitive to both collision energy and isotopic substitution.

#### B) Observation of $CH_3O$ Product in the Crossed Beam Study of the $O(^1D) + CH_4$ Reaction.

The reaction of  $O(^1D)$  and  $CH_4$  is understood to proceed along two distinct pathways: a) by insertion of  $O(^1D_2)$  into the C-H bond to form "hot" methanol, which fragments in the absence of stabilizing collisions; and b) by abstraction of H atoms to form OH and  $CH_3$  radicals. Uncertainty remains as to how the "hot" methanol decomposes. It is suggested that in addition to forming  $CH_3$  and OH by breaking the C-O bond, the other important channel is the elimination of  $H_2$  forming  $H_2CO$ . In this crossed molecular beams study, it is shown that formation of  $H_2 + H_2CO$  is in fact negligible in comparison with the more important channel,  $CH_3O + H$ .

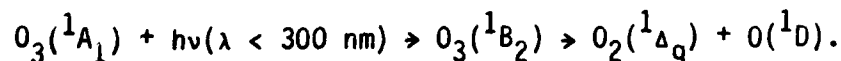
C) The Crossed Beam Reaction of Atomic Oxygen with ICl and CF<sub>3</sub>I

An RF-discharge, supersonic oxygen atom beam source has been used to study the reactions of O + ICl and CF<sub>3</sub>I. The IO bond strength determined from the product flux distribution in the ICl reaction, is  $55.0 \pm 2.0$  kcal mol<sup>-1</sup>, in modest agreement with an earlier measurement. The product from the CF<sub>3</sub>I reaction differs in angular and velocity distribution from that of a previous study, and is found to agree well with statistical calculations using a long-lived complex model.

4) Primary Photodissociation of Polyatomic Molecules

A) Ozone Photolysis: A Determination of the Electronic and Vibrational State Distributions of Primary Products

Since photodissociation mechanisms are poorly understood for systems other than diatomics, we chose ozone as a suitable molecule to study. Extensive theoretical and spectroscopic efforts have been made by other workers which renders a base of information complementary to our studies. The photolysis of ozone is important not only from a theoretical view but also as an important source of metastable O(<sup>1</sup>D) atoms in the atmosphere. The quantum efficiency for production of O(<sup>1</sup>D) has been estimated to be unity for the process



We find, however, that there is an important contribution from previously unseen ground state products. We find at  $\lambda=266$  nm the quantum efficiency for production of  $O(^3P) + O_2(^3\Sigma_g)$  to be 12 percent. This neglected product channel can be significant in quantitative atmospheric modeling calculations.

B) On the Photodissociation of Nitromethane at 266 nm

In a crossed laser-molecular beam study of nitromethane, it was found that the excitation of nitromethane at 266 nm did not yield dissociation products with a quantum yield of  $>3$  percent under collision free conditions. When a small cluster of nitromethane was excited at the same frequency, product was seen only at energies and masses consistent with the rupture of the van der Waals bond by vibrational predissociation of the excited state.

C) Methylene Singlet-Triplet Energy Splitting by Molecular Beam Photodissociation

The singlet-triplet splitting in methylene has been determined from the measurements of fragment velocities from ketene photodissociation at 351 and 308 nm in a molecular beam. The splitting is found to be  $8.5 \pm 0.8$  kcal/mole. This agrees with many experimental results, but not with the value of 19.5 kcal/mole derived from recent photodetachment experiments on  $CH_2^-$ .

D) Competing Dissociation Channels in the Infrared Multiphoton  
Decomposition of Ethyl Vinyl Ether

Infrared multiphoton decomposition of ethyl vinyl ether (EVE) has been investigated by the crossed laser-molecular beam technique. Competition is observed between the two lowest-energy dissociation channels: (1)  $\text{EVE} \rightarrow \text{CH}_3\text{CHO} + \text{C}_2\text{H}_4$ , and (2)  $\text{EVE} \rightarrow \text{CH}_2\text{CHO} + \text{C}_2\text{H}_5$ . Center-of-mass product translational energy distributions were obtained for both dissociation channels. The products of reactions (1) and (2) are formed with mean translational energy of 31 and 5 kcal/mole, respectively. The branching ratio shifts dramatically in favor of the higher energy radical producing channel as the laser intensity and energy fluence are increased, in agreement with the qualitative predictions of statistical unimolecular rate theory.

E) Energy Partitioning to Product Translation in the Infrared Multiphoton  
Dissociation of Diethyl Ether

The infrared multiphoton decomposition of diethyl ether (DEE) has been investigated by the crossed laser-molecular beam technique. The center-of-mass product translational energy distributions ( $P(E')$ ) were measured for the two dissociation channels: (1)  $\text{DEE} \rightarrow \text{C}_2\text{H}_5\text{O} + \text{C}_2\text{H}_5$  and (2)  $\text{DEE} \rightarrow \text{C}_2\text{H}_5\text{OH} + \text{C}_2\text{H}_4$ . The shape of the  $P(E')$  measured for the radical channel (1) is in agreement with the predictions of statistical unimolecular rate theory. The translational energy released in the concerted reaction (2) peaks at 24 kcal/mole; this exceedingly high translational energy release with a relatively narrow distribution results from the recoil

of the products from each other down the exit barrier. Applying statistical unimolecular rate theory, the average energy levels from which DEE dissociates to products are estimated using the measured  $P(E')$  for the radical channel (1).

F) The Photodissociation of Nitromethane at 193 nm

The dissociation of nitromethane following the excitation of the  $\pi^* \leftarrow \pi$  transition at 193 nm has been investigated by two independent and complementary techniques, product emission spectroscopy and molecular beam photofragment translational energy spectroscopy. The primary process is shown to be cleavage of the C-N bond to yield  $\text{CH}_3$  and  $\text{NO}_2$  radicals. The translational energy distribution for this chemical process indicates that there are two distinct mechanisms by which  $\text{CH}_3$  and  $\text{NO}_2$  radicals are produced. The dominant mechanism releasing a relatively large fraction of the total available energy to translation probably gives  $\text{NO}_2$  radicals in a vibrationally excited  $^2\text{B}_2$  state. When dissociated, other nitroalkanes exhibit the same emission spectrum as  $\text{CH}_3\text{NO}_2$ , suggesting little transfer of energy from the excited  $\text{NO}_2$  group to the alkyl group during dissociation for the dominant mechanism. This conclusion is supported by the apparent loss of the slow  $\text{NO}_2$  product in the molecular beam studies to unimolecular dissociation to  $\text{NO} + \text{O}$ , which will occur for  $\text{NO}_2$  with 72 kcal/mole or more internal energy.

Evidence is presented which suggests that the  $\text{NO}_2$  produced via the minor mechanism, which releases a smaller fraction of the available energy to translation, has a large cross section for absorbing an additional photon via a parallel transition and dissociating to  $\text{NO} + \text{O}$ .



List of Publications of ONR Supported Research

1. Crossed Molecular Beam Study of  $F + CH_3I$ , J. M. Farrar and Y. T. Lee, J. Chem. Phys. 63, 3639 (1975).
2. Iodine-Fluorine Bond Strength in IIF, ClIF, and HIF, J. J. Valentini, M. J. Coggiola, and Y. T. Lee, J. Am. Chem. Soc. 98, 853 (1976).
3. Molecular Beam Study of  $F_2 + I_2$ , M. J. Coggiola, J. J. Valentini, and Y. T. Lee, Int. J. Chem. Kin. 8, 605 (1976).
4. The Question of Energy Randomization in the Decomposition of Chemical Activated  $C_2H_4F$ , J. M. Farrar and Y. T. Lee, J. Chem. Phys. 65, 1414 (1976).
5. Crossed Beam Studies of Endoergic Bimolecular Reactions: Production of Stable Trihalogen Radicals, J. J. Valentini, M. J. Coggiola, and Y. T. Lee, Faraday Discussion on Potential Energy Surfaces, University of Sussex, England, 62, (1976).
6. Photoionization with Molecular Beams: I. Autoionization Structure of Nitric Oxide Near the Threshold, C. Y. Ng, B. H. Mahan, and Y. T. Lee, J. Chem. Phys. 65, 1956 (1976).
7. The Binding Energy Between NO and  $NO^+$ , C. Y. Ng, P. W. Tiedemann, B. H. Mahan, and Y. T. Lee, J. Chem. Phys. 66, 3985 (1977).
8. Photoionization Studies of the  $Kr_2$  and  $Ar_2$  van der Waals Molecules, C. Y. Ng, D. J. Trevor, B. H. Mahan, and Y. T. Lee, J. Chem. Phys. 66, 446 (1977).
9. Supersonic Atomic and Molecular Halogen Nozzle Beam Source, James J. Valentini, Michael J. Coggiola, and Yuan T. Lee, Rev. Sci. Instrum. 48, 58 (1977).

10. Photoionization Studies of the Diatomic Heteronuclear Rare Gas Molecules XeKr, XeAr, and KrAr, C. Y. Ng, P. W. Tiedemann, B. H. Mahan, and Y. T. Lee, J. Chem. Phys. 66, 5737 (1977).
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12. Molecular Beam Studies of Unimolecular Reactions:  $\text{Cl}, \text{F} + \text{C}_2\text{H}_3\text{Br}$ , Richard J. Buss, Michael J. Coggiola, and Yuan T. Lee, Farad. Disc. Chem. Soc. 67, 162 (1979).
13. Ozone Photolysis: A Determination of the Electronic and Vibrational State Distributions of Primary Products, R. K. Sparks, L. R. Carlson, K. Shobatake, M. L. Kowalczyk, and Y. T. Lee, J. Chem. Phys. 72, 1401 (1980).
14. Development of a Supersonic  $\text{O}(^3\text{P}_j)$ ,  $\text{O}(^1\text{D}_2)$  Atomic Oxygen Nozzle Beam Source, Steven J. Sibener, Richard J. Buss, Cheuk-Yiu Ng, and Yuan T. Lee, Rev. Sci. Instr. 51, 167 (1980).
15. A Crossed Molecular Beams Investigation of the Reactions of  $\text{O}(^3\text{P}) + \text{C}_6\text{H}_6$ ,  $\text{C}_6\text{D}_6$ , Steven J. Sibener, Richard J. Buss, Piergiorgio Casavecchia, Tomohiko Hirooka, and Yuan T. Lee, J. Chem. Phys. 72, 4341 (1980).
16. Observation of  $\text{CH}_3\text{O}$  Product in the Crossed Beam Study of the  $\text{O}(^1\text{D}) + \text{CH}_4$  Reaction, P. Casavecchia, R. J. Buss, S. J. Sibener, and Y. T. Lee, J. Chem. Phys. 73, 6351 (1980).

17. On the Photodissociation of Nitromethane at 266 nm, H. S. Kwok, G. Z. He, R. K. Sparks, and Y. T. Lee, J. Chem. Kinet. 13, 1125 (1981).
18. Methylene Singlet-Triplet Energy Splitting by Molecular Beam Photodissociation of Ketene, Carl C. Hayden, Daniel M. Neumark, Kosuke Shobatake, Randal K. Sparks, and Yuan T. Lee, J. Chem. Phys. 76, 3607 (1982).
19. Competing Dissociation Channels in the Infrared Multiphoton Decomposition of Ethyl Vinyl Ether, F. Huisken, D. Krajnovich, Z. Zhang, Y. R. Shen, and Y. T. Lee, J. Chem. Phys. 78, 3806 (1983).
20. The Photodissociation of Nitromethane at 193 nm, L. J. Butler, D. Krajnovich, Y. T. Lee, G. Ondrey, and R. Bersohn, J. Chem. Phys. 79, 1708 (1983).
21. Energy Partitioning to Product Translation in the Infrared Multiphoton Dissociation of Diethyl Ether, L. J. Butler, R. J. Buss, R. J. Bruozynski, and Y. T. Lee, J. Phys. Chem. (1983) in press.

Invited Lectures Presented During the Contract Period

1. Y. T. Lee, Molecular Beam Chemistry of Fluorine Containing Radicals, Symposium on Fluorine Containing Radicals, 169th ACS National Meeting, Philadelphia, April 6-11, 1975.
2. Y. T. Lee, Studies in Chemical Dynamics, Annual Conference on Mass Spectrometry and Allied Topics, Houston, Texas, May 1975.
3. Y. T. Lee, Reactive Scattering of  $F_2$  and  $I_2$ , IXth International Conference on the Physics of Electronic and Atomic Collisions, Seattle, Washington, July 24-30, 1975.
4. Y. T. Lee, Energetics and Dynamics of Elementary Chemical Reactions, Chemistry Department, California Institute of Technology, Pasadena, California, February 19, 1975.
5. Y. T. Lee, Radical Chemistry by the Molecular Beams Method, Stanford Research Institute, Stanford, California, October 16, 1975.
6. Y. T. Lee, Formation and Decomposition of Radical Molecules, Chemistry Department, University of California, Davis, October 28, 1975.
7. Y. T. Lee, Crossed Molecular Beam Studies on Atomic and Molecular Interactions, Western Spectroscopy Association, 23rd Annual Conference, Asilomar, California, January 28-30, 1976.
8. Y. T. Lee, Recent Studies on Radical Molecules, University of Chicago, Department of Chemistry, Chicago, Illinois, March 1, 1976.
9. Y. T. Lee, Molecular Beam Studies on Reaction Dynamics, TAM-ACS Joint Centennial Symposium on Chemistry, Texas A & M University, College Station, Texas, March 15-16, 1976.
10. Y. T. Lee, Crossed Molecular Beam Chemical Kinetics, Chinese University of Hong Kong, June 9, 1976.
11. Y. T. Lee, Studies of Reaction Dynamics by the Molecular Beams Method, Institute of Nuclear Studies, Taiwan, June 16, 1976.
12. Y. T. Lee, Dynamics of Chemical Reactions, Department of Chemistry, University of Tokyo, Japan, June 23, 1976.
13. Y. T. Lee, Molecular Beam Isotope Separations, Symposium on Isotope Separation, American Chemical Society Meeting, San Francisco, California, August 30, 1976.

14. Y. T. Lee, Energy Distribution in Products of Bimolecular Reactions, a joint meeting on "Energy Transfer Processes in Chemical Reactions" by the Faraday Division of the Chemical Society, the Societe de Chimie - Physique, the Associazione di Chimica Fisica and the Deutsche Bunsengesellschaft, Konigstein, West Germany, September 12-18, 1976.
15. Y. T. Lee, High Energy Collision Between Atoms and Molecules, California Institute of Technology, Pasadena, July 16, 1976.
16. Y. T. Lee, Synthesis and Energetics of Radicals by Crossed Molecular Beams Method, 12th International Symposium on Free Radicals, Laguna Beach, California, January 5-9, 1976.
17. Michael J. Coggiola, Crossed Beam Studies of Endoergic Bimolecular Reactions: ~~Production of Stable Trihalogen Radicals, Faraday~~ Discussion on Potential Energy Surfaces, University of Sussex, England, September 8-10, 1976.
18. Y. T. Lee, Molecular Beam Studies on Dynamics of Infrared Multiphoton Dissociation of Polyatomic Molecules, University of California, Berkeley, Department of Chemistry, February 8, 1977.
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25. Y. T. Lee, Recent Studies on Interaction of Photons with Molecules by the Molecular Beams Method, Max-Planck-Institute für Stromungsforschung, Göttingen, West Germany, May 6, 1977.

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29. Y. T. Lee, Dynamics of Infrared Multiphoton Excitation and Dissociation of Polyatomic Molecules, JILA-Battelle Laser Workshop, Seattle, Washington, August 22, 1977.
30. Y. T. Lee, Molecular Beam Studies on the Dynamics of Multiphoton Dissociation of Polyatomic Molecules, Department of Chemistry, University of California, Santa Cruz, California, October 19, 1977.
31. Y. T. Lee, Molecular Beam Photoionization Spectroscopy, Department of Chemistry, Tohoku University, Sendai, Japan, December 19, 1977.
32. Y. T. Lee, Crossed Molecular Beam Chemical Kinetics, College of General Education, University of Tokyo, Japan, December 22, 1977.
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34. Y. T. Lee, Recent Advancement of Molecular Beams Experiments, Department of Chemistry, University of Kyoto, Japan, December 24, 1977.
35. Y. T. Lee, Laser Induced Chemistry by a High Power CO<sub>2</sub> Laser, Department of Chemistry, Tsinghua University, Taiwan, China, December 29, 1977.
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53. Y. T. Lee, Interaction Potentials and Molecular Collisions, Haverford College, Haverford, Pennsylvania, November 8, 1978.
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55. Y. T. Lee, Laser Induced Unimolecular Decomposition, Haverford College, Haverford, Pennsylvania, November 10, 1978.
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57. Y. T. Lee, Dynamics of Infrared Multiphoton Dissociation of Polyatomic Molecules, Department of Chemistry, Rice University, Houston, Texas, March 7, 1979.
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61. R. J. Buss, Molecular Beam Studies of Unimolecular Reactions,  $\text{Cl}$ ,  $\text{F} + \text{C}_2\text{H}_3\text{Br}$ , Faraday General Discussion No. 67, "Kinetics of State-Selected Species," University of Birmingham, England, April 9-11, 1979.
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64. Y. T. Lee, Intramolecular Energy Transfer of Vibrationally Excited Molecules, Naval Weapons Laboratory, Washington, D.C., May 23, 1979.
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70. Y. T. Lee, Molecular Beam Studies of Elementary Chemical Reactions, Summer School on Chemical Photophysics, Les Houches, France, June 27, 1979.
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72. Y. T. Lee, Photoionization and Vibrational Predissociation of van der Waals Molecules, Herzberg International Conference on van der Waals Molecules, Quebec, Canada, August 1-3, 1979.
73. Y. T. Lee, Dynamics of Multiphoton Excitation Processes, Symposium on Atomic and Molecular Science, Taipei, China, August 23-25, 1979.
74. Tomohiko Hirooka, A Crossed Molecular Beam Study of the Reactions of  $O(^3P) + C_6H_6, C_6D_6$ , XI International Conference on the Physics of Electronic and Atomic Collisions, Kyoto, Japan, August 29-September 4, 1979.
75. K. Shobatake, Energy Disposal in the Photodissociation of  $CH_3I$  at 266 nm, XI International Conference on the Physics of Electronic and Atomic Collisions, Kyoto, Japan, August 29-September 4, 1979.
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79. Y. T. Lee, Reaction of Oxygen Atoms with Unsaturated Hydrocarbons, Harvard-MIT Joint Physical Chemistry Seminar, Cambridge, Massachusetts, March 13, 1980.
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81. Y. T. Lee, Reaction of Oxygen Atoms with Unsaturated Hydrocarbons, Department of Chemistry, Columbia University (Falk-Plaut Lectures) April 16, 1980.
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86. Y. T. Lee, Photodissociation of Molecules by High Power Lasers, Eyring Symposium, University of Utah, Salt Lake City, Utah, June 13, 1980.
87. Y. T. Lee, Lecture series on Chemical Kinetics and Reaction Dynamics, Institute of Chemistry, Beijing, China, June 23-July 12, 1980.
88. Y. T. Lee, Lecture series on Molecular Beam Chemical Kinetics, Institute of Chemical Physics, Dalian, China, July 26-30, 1980.
89. Y. T. Lee, Photofragmentation Translational Spectroscopy of Ozone and Methyl Iodide, Institute of Optics, Shanghai, China, July 22, 1980.
90. Y. T. Lee, Dynamics of Infrared Multiphoton Dissociation of Polyatomic Molecules, Shanghai Science Association, Shanghai, China, July 23, 1980.
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94. Y. T. Lee, Photodissociation of Ketene: Singlet-Triplet Energy Splitting of Methylene, Joint Physics and Chemistry Department Colloquium, University of Oregon, Eugene, Oregon, November 6, 1980.
95. Y. T. Lee, Recent Advances of Photofragmentation Translational Spectroscopy, Western Spectroscopy Association Conference, Asilomar, Pacific Grove, California, January 28-30, 1981.
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97. Y. T. Lee, Crossed Molecular Beam Studies of Elementary Atomic and Molecular Processes, Lester Kuhn Memorial Lecture, Department of Chemistry, Johns Hopkins University, Baltimore, Maryland, March 17, 1981.
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99. Y. T. Lee, Dynamics of Endothermic Reactions Involving Atoms and Polyatomic Molecules, Debye Award Symposium honoring Professor R. B. Bernstein, American Chemical Society Annual Meeting, Atlanta, Georgia, March 30, 1981.
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104. Y. T. Lee, Photofragmentation Translational Spectroscopy, Academia Sinica, Taiwan, China, May 29, 1981.

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106. Y. T. Lee, The Current Status of the Reactive Scattering Experiment, XII International Conference on the Physics of Electronic and Atomic Collisions, Gatlinburg, Tennessee, July 15-21, 1981.
107. Y. T. Lee, Current Status of Reactive Scattering, Gordon Research Conference on "Dynamics of Molecular Collisions" at Plymouth, New Hampshire, July 27-31, 1981.
108. Y. T. Lee, The Effect of Vibrational Excitation in Ion-Molecule Reactions, 28th International Union of Pure and Applied Chemistry Congress, ~~Vancouver, Canada, August 17-22, 1981.~~
109. Y. T. Lee, Reactions of Oxygen Atoms with Ethylene and Vinylbromide, X International Conference on Photochemistry, The University of Crete, Iraklion, Crete, Greece, September 9-12, 1981.
110. Y. T. Lee, Molecular Beam Studies of Bimolecular Reactions:  $F + H_2$  and  $Li + HF$ , 50 Years Dynamics of Chemical Reactions Conference, Berlin, West Germany, October 12-15, 1981.
111. Yuan T. Lee, Molecular Beam Chemistry, Chinese Institute of Engineers Annual Meeting, San Francisco, California, January 30, 1982.
112. Yuan T. Lee, Dynamic Resonance Phenomena on Reactive Scattering, Department of Chemistry, University of California, Irvine, California, March 8, 1982.
113. Yuan T. Lee, Vibrational and Translational Energy Dependence in Reactions of  $H_2^+$ , American Chemical Society Meeting, Las Vegas, Nevada, March 30-April 1, 1982.
114. R. J. Buss,  $O(^3P)$  Reactions with Unsaturated Hydrocarbons, Mechanism and Dynamics, American Chemical Society Symposium, Chemical Kinetics of Combustion, Las Vegas, Nevada, March 28-April 1, 1982.
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116. Yuan T. Lee, Molecular Beam Studies of Reaction Mechanism and Photochemical Processes, Department of Chemistry, University of Pittsburgh, Pittsburgh, Pennsylvania, May 19, 1982.
117. Yuan T. Lee, Reaction of Oxygen Atoms with Unsaturated Hydrocarbons, International Symposium on Chemical Kinetics Related to Atmospheric Chemistry, Tsubuka Science Center, Tsubuka, Japan, June 6-10, 1982.

118. Yuan T. Lee, Molecular Beam Studies on Elementary Reactions and Photochemical Processes, Symposium on Reaction Dynamics, Institute for Molecular Sciences, Okazaki, Japan, June 12, 1982.
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121. Yuan T. Lee, Primary Photochemical Processes, Institute of Chemistry, Beijing, China, June 23, 1982.
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124. Yuan T. Lee, Molecular Beam Investigation on Laser Chemistry, Department of Chemistry, Fudan University, Shanghai, China, June 28, 1982.
125. Yuan T. Lee, The Use of Vacuum UV photons in the Investigation of Energetics and Dynamics of Elementary Reactions, University of Taiwan, Taiwan, July 14-30, 1982.
126. Carl C. Hayden,  $F + H_2$  Reactive Scattering Experimental Results, Gordon Research Conference on Atomic and Molecular Interactions, New London, New Hampshire, July 25-30, 1982.
127. R. J. Buss, The Study of High Energy Collisions in Molecular Beams, 11th International Hot Atom Chemistry Symposium, University of California, Davis, California, August 16-21, 1982.
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130. Yuan T. Lee, Molecular Beam Photofragmentation Studies of Simple Polyatomic Molecules, Wayne State University, October 11, 1982.

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132. Yuan T. Lee, Molecular Beam Studies of Primary Photochemical Processes of Organic Molecules, Department of Chemistry, University of Utah, Salt Lake City, Utah, December 7, 1982.
133. Yuan T. Lee, Molecular Beam Chemical Kinetics, Golden Jubilee of Chinese Chemical Society Located in Taipei, Taipei, Taiwan, China, December 12, 1982.
134. Y. T. Lee, Primary Photochemical Processes by Molecular Beam Photofragmentation Translational Spectroscopy, International Conference on Photochemistry and Photobiology, January 3-8, 1983, Alexandria, Egypt.
135. Y. T. Lee, Crossed Molecular Beams Studies Using the Seeded Supersonic Beams Method, John Fenn Symposium, Yale University, March 14-15, 1983.
136. Y. T. Lee, Dynamic Resonances in Reactive Scattering, Department of Chemistry, Rice University, March 16, 1983.
137. Y. T. Lee, Elucidation of Reaction Mechanism by the Crossed Molecular Beams Method, Kolthoff Lecture, Department of Chemistry, University of Minnesota, April 25, 1983.
138. Y. T. Lee, Molecular Beam Studies of Primary Photochemical Processes, Kolthoff Lecture, Department of Chemistry, University of Minnesota, April 27, 1983.
139. Y. T. Lee, Dynamic Resonances in  $F + H_2$  Reaction, Kolthoff Lecture, Department of Chemistry, University of Minnesota, April 29, 1983.
140. Y. T. Lee, High Brilliance VUV Photochemistry, Workshop on Synchrotron Radiation Source, Lawrence Berkeley Laboratory, May 10, 1983.
141. Y. T. Lee, The Effect of Internal Excitation in Promoting a Chemical Reaction, Workshop on Elementary Chemical Reactions, University of Paris, Orsay, France, June 10, 1983.
142. Y. T. Lee, Recent Advances in Molecular Beam Chemistry, Workshop on Elementary Chemical Reactions, University of Paris, Orsay, France, June 10, 1983.
143. Y. T. Lee, Reactive Scattering, Advances and Perspectives, International Symposium on Molecular Beams, Freiburg, West Germany, June 13-17, 1983.

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